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Informational aspects at model of power consumption by main drainage facilities of iron-ore mining enterprises

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ABSTRACT

The work investigates into variable informational approaches to modeling power consumption by main drainage facilities of ore mining enterprises with underground mining method. Methodological recommendations for using the models are also designed. The research deals with general methodological approaches to model formation with both power consumption indices for drainage facilities and corresponding costs. Logistics of model formation is substantiated, namely, combination of classic multifactor regression modeling with modern digital modeling methods – automated control systems used for drainage facilities. Principles of building fuzzy logic controllers and algorithms of their functioning under multichannel control are determined in detail. The improved fuzzy logic-based variant is proposed and combined, with correlation analysis, to provide the basis for developing algorithms of the automated control systems of electric power consumption. There is an example of developing a "road map" for implementing a generalized algorithm for automated control systems power flows for two current cases – a selective tariff with limited daily contract-based power consumption and that with a variable tariff. It is established that application of the two-rate hourly tariff with its conditional distribution (Night/Peak) instead of the three-rate tariff (Night/Half-Peak/Peak) on a single-use basis leads to a thirteen percent increase of daily power costs with a single-channel control of the ore flow and a seven percent increase with two-channel control (ore flow and drainage simultaneously). The use of fuzzy logic controllers enables minimizing these losses.

Keywords: Fuzzy logic; correlation analysis; iron-ore enterprise; main drainage facilities; electric power consumption; multifactor regression modeling

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INTRODUCTION

The mining and metallurgical industry forms economies of major mining countries. However, while a few decades ago, the metallurgical component dominated in this economic tandem, the mining sector is taking the lead at present [1]. Economies of both Ukraine and other iron ore exporters are noted for adverse, factors including mineral costs on the international raw material market, which are not constant and characterized by instability and up-down fluctuations.

At the same time, the cost of mineral mining is constantly growing for a number of objective and subjective reasons [2, 3].

Increased costs for iron ore mining are mostly due to the energy component with the power factor dominating [4]. This is caused by the fact that iron ore enterprises, like the entire mining and metallurgical industry, are energy-intensive, this greatly complicating prospects for their economic development with continually growing prices for energy-carriers for consumers. Power load imposed on mining enterprises is determined by the mining technology applied – both open pit and underground methods – that causes a constant increase of mining depths which a priori rejects any positive prospects to substantially reduce power consumption at these types of enterprises.

The above in no way challenges the need for and efficiency of certain trivial measures aimed to improve energy efficiency of iron ore production, but the search for effective modern options in this direction is more crucial for achieving tangible levels of mining enterprises' performance.

However, it should be, noted that the existing in-pit crushing and conveying technology of mining enterprises and their power consumers allows transforming time-of-day power consumption from the *consumer* option into the *consumer-controller* one. Underground mining enterprises have a limited number of energy-intensive consumers, this fact contributing greatly to solving this problem [4]. The latter, in turn, consume 80%-85% of these enterprises' total power.

According to [4], among various energy-intensive consumers in iron ore underground mining, one should highlight main drainage facilities, which dominate among others, consuming 18%-27% of the total power consumed by these types of enterprises.

THE AIM OF THE ARTICLE

The research aims to investigate into variable approaches to logistics of adequate modeling of power consumption by drainage facilities of iron ore underground enterprises and develop a schematic-analytical "road map" to implement the developed options for creating a cost control algorithm.

LITERATURE REVIEW

Among well-known scientific works aimed at improving energy efficiency of main drainage facilities, there are two substantial ways to solve the problem. The former is automation of controlling operation of electromechanical complexes of main drainage facilities without changing the existing structure of drainage. This solution targets the level of water inflow in the main in-take area and operation modes of drainage facilities with daily tariffs of power consumption. The latter is, aimed at transferring drainage facilities from the *consumer* class to the *consumer-controller* one. At the same time, the structure of groundwater drainage remains unchanged. However, in real time, transformation of this structure into the *power consumer-controller-generator* class looks relevant in the long run.

Thus, [5] provides an original integrated model of a coal mining enterprise designed to evaluate and support effective energy saving solutions. To do this, the model presents an enterprise as a set of four interrelated subsystems. The level of the integrated model provides synchronization of subsystems functioning, which is determined, by power consumption. However, the proposed system does not differentiate energy-intensive consumers of enterprises, and its subsystems reflect only technology components of iron ore mines operation. This approach averages specific features of individual power consumers and does not realize their energy potential.

This very approach is reflected in the works concerning gold mining enterprises [6]. Here the search is aimed at reducing power, consumption by energy-intensive consumers, including water pumps.

The research results on selecting effective operational modes of main drainage facilities in [7] considering drain sump capacity, the number of pumps and underground horizons levels of a mine. The best option of main drainage is selected by choosing effective time-of-day (hourly) zones of performance.

At [8] analyzes ways to improve efficiency of main drainage facilities functioning at coal mines. Yet, technologies of pumping water from underground levels of iron ore mines differ from those used at coal mines. This difference is due to the fact that underground levels of several individual iron ore mines are "enclosed" in a single pumping cycle, while coal mines function exclusively on an individual basis.

Works [9-10], [11-12], [13-14], [15-16], [17-18], [19-20], [21-22], [23-24], [25-26], [27-28], [29-30] presents the research results of developing designs of hydroelectric pumped-storage power plants based on drainage facilities of underground mines and open pits. These works share the same goal – to create power-generating capacities due to their own energy resources. To do this, conditions of individual enterprises are analyzed, with possible designs offered and relevant investments evaluated.

Meanwhile, there are constraints for implementing "pilot" options proposed, including those in the above research works.

The process is complicated by the fact that nowadays methods of calculating main drainage features in iron ore mining are outdated and far from being perfect, this being caused by peculiarities of current functioning of these facilities.

In [30, 31] substantiate and formalize a set of steps for improving electric energy efficiency of main drainage facilities. Besides, there is a preventive structure of automated control, subsystems of this complex incorporated into the structure of the ACS of underground mining enterprise consumers.

Yet, practical implementation of this component in compliance with functional potential of the ACS requires development of an adequate algorithm for its performance with relevant software designed. Logistics of such development will be effective and balanced if adequate control over input parameters and impacts of enterprises' technological factors on them are achieved. This can be, done by modeling.

MATERIALS AND METHODS OF RESEARCH

Mathematical modeling of this complex functioning in the form of stochastic processes is one of possible approaches to developing the ACS algorithm for drainage facilities of iron ore underground enterprises considering peculiarities of underground mining enterprise functioning. Current scientific and practical studies reveal that multiple correlation-regression analysis and analytical correlations are most applicable to characterizing power consumption processes of main drainage facilities, this enabling investigation into potential of theoretical and practical application of these methods.

Basic stages of the suggested multiple regression model include the following components [19]:

1) Parameters of multiple regression equations are assessed by the least square method. For linear equations, the following set of normal equations is built to assess regression parameters:

$$y = a + b_1x_1 + b_2x_2 + \cdots + b_mx_m + \varepsilon\,. \quad (1)$$

In the linear regression, parameters at x characterize the average change in the result with the corresponding factor changed per unit with the constant value of other factors fixed at the mean level.

2) The least square method is applied to the multiple regression equation on the standardized scale.

3) The factors are compared with each other and it is expedient to rank them by their impact on the result. The comparison results in excluding one of the most related factors from further research.

4) Transition from the regression equation on the standardized scale to the regression equation on the natural scale of variables is performed, while the parameter a is defined as:

$$a = \overline{y} - b_1 \cdot \overline{x}_1 - b_2 \cdot \overline{x}_2 - \ldots - b_m \cdot \overline{x}_m. \quad (2)$$

where b_i is a coefficient of "pure" regression.

The considered meaning of standardized regression coefficients enables using them to select factors. The factors with the lowest β_i value are excluded from the model.

5) Average elasticity coefficients for linear regression are, calculated by the following formula:

$$\overline{E_{yx_j}} = b_j \cdot \frac{\overline{x}_j}{\overline{y}}. \quad (3)$$

The coefficients show how the average result changes when the corresponding factor changes by 1%. Average elasticity factors, can be compared, with each other and ranked by their impact on the result.

6) Density of combined influence of all the factors on the result of assessing the multiple correlation indexes is determined:

$$R_{yx_1x_2\ldots x_m} = \sqrt{1 - \frac{\sigma^2_{y_{ocm}}}{\sigma^2_y}}. \quad (4)$$

The multiple correlation index value is between 0 and 1 and should be greater than or equal to the maximum pair correlation index:

$$R_{yx_1x_2\ldots x_m} \geq r_{yx_i}\,(i = \overline{1,m}). \quad (5)$$

7) The corrected multiple determination index which contains correction for the number of freedom degrees is determined and calculated by the formula:

$$\hat{R}^2 = 1 - (1 - R^2) \cdot \frac{(n-1)}{(n-m-1)}, \quad (6)$$

where: n is the number of observations; m is the number of factors.

8) Individual correlation coefficients (or indices) that measure the effect of the factor x_i on y when eliminating the influence of other factors can be calculated by the formula:

$$r_{yx_1 \cdot x_1x_2\ldots x_{i-1}x_{i+1}\ldots x_m} = \sqrt{1 - \frac{1 - R^2_{yx_1x_2\ldots x_m}}{1 - R^2_{yx_1x_{j-1}x_{j+1}\ldots x_m}}}, \quad (7)$$

or by the recurrent formula:

$$r_{yx_1 \cdot x_1x_2\ldots x_{i-1}x_{i+1}\ldots x_m} = \frac{r_{yx_1 \cdot x_1x_2\ldots x_{i-1}x_{i+1}\ldots x_{m-1}} - r_{yx_m \cdot x_1x_2\ldots x_{m-1}} \cdot r_{x_1x_m \cdot x_1x_2\ldots x_{i-1}x_{i+1}\ldots x_{m-1}}}{\sqrt{(1 - r_{yx_m \cdot x_1x_2\ldots x_{m-1}}) \cdot (1 - r_{x_1x_m \cdot x_1x_2\ldots x_{i-1}x_{i+1}\ldots x_{m-1}})}}. \quad (8)$$

Individual correlation factors determine the relationship degree for each factor with the result in its pure form without considering the influence of other factors.

9) Significance of the multiple regression equation as a whole is assessed by means of the F-criterion:

$$F = \frac{R^2}{1-R^2} \cdot \frac{n-m-1}{m}. \quad (9)$$

10) The individual F-criterion assesses the statistical significance of the presence of each of the factors in the equation. In general, for the factor x, the individual F-criterion is determined as:

$$F_{x_i} = \frac{R^2_{yx_1x_2\ldots x_m} - R^2_{yx_1x_{j-1}x_{j+1}\ldots x_m}}{1-R^2_{yx_1x_2\ldots x_m}} \cdot \frac{n-m-1}{m}. \quad (10)$$

The actual value of the individual F-criterion is compared with the table value at the significance level α and freedom degrees: $k_1=1$; $k_2=n-m-1$.

If the actual value of F_{xi} exceeds the theoretical $F(\alpha, k_1, k_2)$, additional inclusion of the factor x_i into the model is statistically justified and the pure regression coefficient b_i with the factor x_i is statistically significant.

11) Significance of pure regression coefficients is assessed by the Student t-criterion. In this case, as in pair regression, the following formula is used for each factor:

$$t_{b_i} = \frac{b_i}{m_{b_i}}. \quad (11)$$

12) For the multiple regression equation, the mean square error of the regression coefficient can be determined by the formula:

$$m_{b_i} = \frac{\sigma_y \cdot \sqrt{1-R^2_{yx_1x_2\ldots x_m}}}{\sigma_{x_i} \cdot \sqrt{1-R^2_{x_1x_2\ldots x_m}}} \cdot \frac{n-m-1}{m}, \quad (12)$$

where $R^2_{x_1x_2\ldots x_m}$ is the determination coefficient for dependence of the factor x_i with all other factors.

On the basis of the calculated indices of inter-factor correlation of the model, non-essential factor features are determined and removed from further research. Thus, a new model is built, which includes significant factor features with new pre-calculated regression parameters. On the basis of the new model, conclusions are drawn about the effect of the features on the resulting index.

Analytical ratios are suggested to be based on the energy conservation law. To lift water from the underground level of a mine, it is necessary to perform some elementary work [20].

$$da = g \cdot h \cdot dm, \quad (13)$$

where: dm – is an element of the water mass, kg; g – is free fall acceleration, m/s^2;
h is the depth from which water is pumped out, m.

If the volume of water is considered, formula (13) takes the form

$$da = \rho \cdot g \cdot h \cdot du, \quad (14)$$

where: ρ – is water density kg/m^3;
du – is an element of the water volume, m^3.

To convert energy into kW*h we use the following coefficient

$$\delta = 2.78 \cdot 10^{-7} \text{ kW*h/J}.$$

Then formula (14) has the form

$$da = \rho \cdot g \cdot h \cdot \delta \cdot du. \quad (15)$$

In its turn, considering the values $\rho=10^3$ kg/m^3, g= 9.8 m / sec^2, formula (15) has the form

$$da = \beta \cdot h \cdot du, \quad (16)$$

where $\beta = \rho \cdot g \cdot \delta = 0.002724$ N/m^3.

Formula (16) enables calculating the work required to lift the element of the water volume du to the height h.

Considering that

$$du = v(t)dt,$$

where is the velocity of water accumulation at the moment t, m^3/h.

Formula (16) will look like

$$da = \beta \cdot h \cdot v(t)dt. \quad (17)$$

Then the dependence of power consumption capacity for water lifting will be determined by the formula

$$n(t) = \beta \cdot h \cdot v(t), \quad (18)$$

where $n(t) = \frac{da(t)}{dt}$ is power capacity, kW.

It should be noted that the above analytical correlations (13-18) do not consider efficiency of pumps, as this indicator corresponds to actual values of individual pumps to be used.

At the same time, it should be emphasized that in real-life conditions the water accumulation rate on the underground level is a stochastic function, as at each moment of time it is caused by different pre-unknown reasons [26]. Introduction of stochastic components complicates analytical description and requires additional modeling.

To do this, the authors have conducted studies to obtain certain multiple regression models.

DEVELOPMENT OF THE ACS OF ELECTRIC POWER CONSUMPTION BY DRAINAGE FACILITIES IN IRON ORE UNDERGROUND MINING

Today, there is a need for digitalization of decision-making by modern automation methods. The authors believe that use of *the ACS of electric power consumption* is one of solutions.

Fig. 1 presents the basic algorithm of the subsystem *ACS of drainage facilities* functioning.

It should be noted that in this period at most, if not at all, enterprises, a number of preventive solutions have been implemented, this providing the basis for creating *the ACS of electric power consumption*.

At the same time, basic tasks of building the ACS should include integrity of its functioning by optimizing power consumption (electricity consumption, corresponding costs) at iron ore underground mines when using appropriate hourly tariffs for power consumed and, on the other hand, the ability to increase the number of impact criteria to expand functions of the control system.

To simplify perception of developing the ACS algorithm we conventionally, in the first approximation, narrow the number of time-of-day tariffs to two zones – peak/non-peak. As confirmed later, this will not cause any tangible deviations to the final result of developing the functioning algorithm of the ACS (Fig. 2).

In the first approximation, *the ACS* of electric power consumption algorithm includes nine blocks.

Block 1 informs about the start of ACS operation.

Block 2 actualizes the current regulatory base of Ukraine for power consumption and supply. Here, initial information on current parameters is input according to current criteria of control and problem statement.

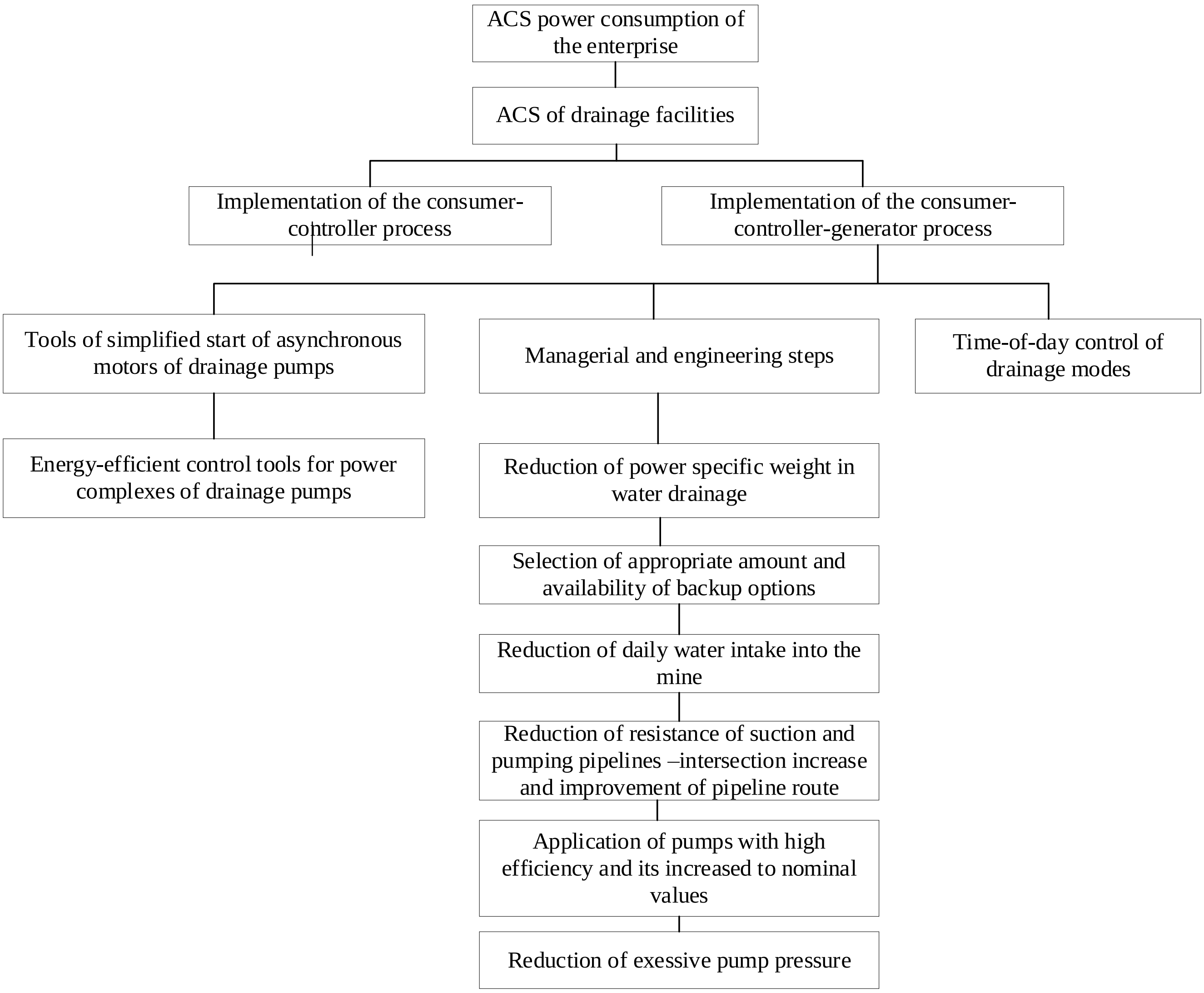

Fig. 1. **Basic algorithm of the subsystem *ACS* of drainage facilities functioning**
Source: **compiled by the authors**

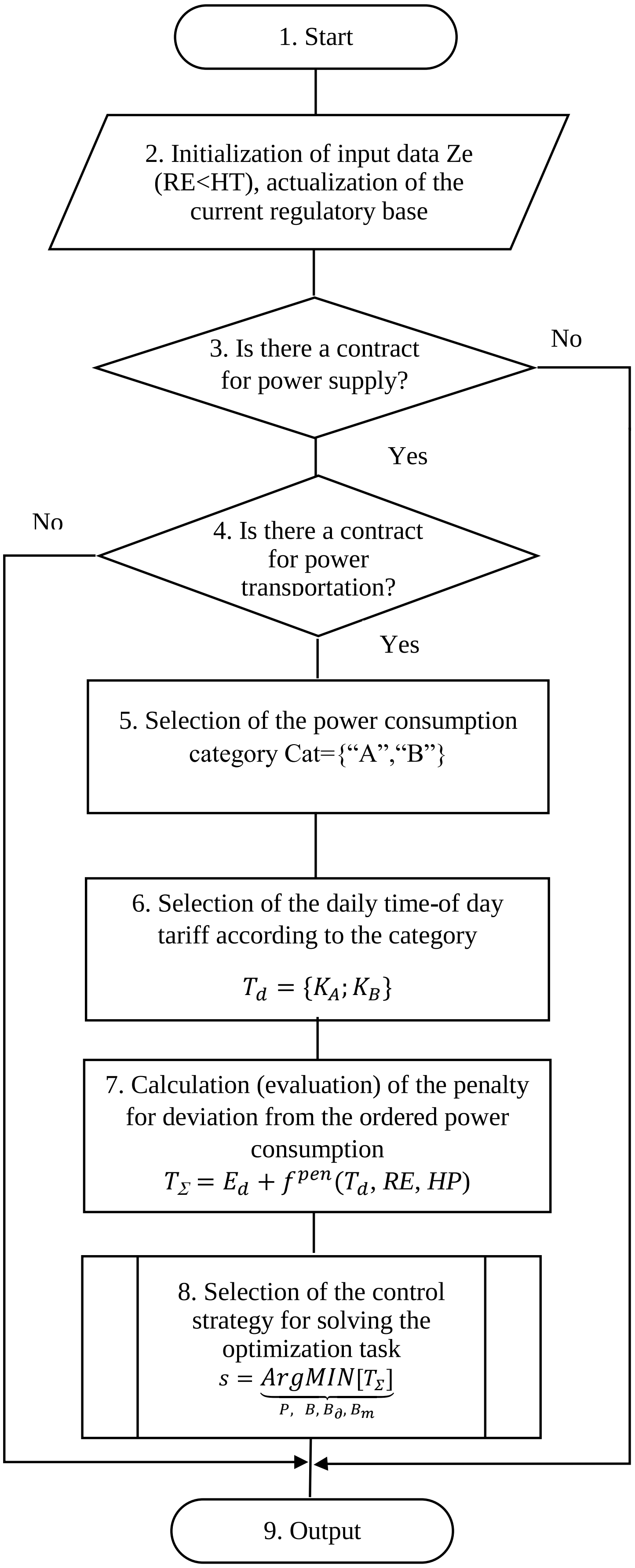

Fig. 2. **General algorithm of the ACS of electric power consumption functioning**
Source: **compiled by the authors**

With this in mind, we should determine potential control criteria as (19) - (23)

$$Z^e = F\left(RE, HT\right) \Rightarrow \min, \quad (19)$$

$$P \Rightarrow \max, \quad (20)$$

$$B \Rightarrow \max, \quad (21)$$

$$B_\partial \Rightarrow \max, \quad (22)$$

$$B_m \Rightarrow \max, \quad (23)$$

where: Z^e is the enterprise's total costs for electricity (hourly, daily), UAH; *RE* is power consumption (hourly, daily), kW*h; *HT* is the current tariff for electricity, UAH/kW*h; $F\left(\bullet\right)$ is some established functional dependence; *P* is ore output at the enterprise (hourly, daily), t; *B* is air supply (hourly, daily), m^3; B_∂ is the volume of pumped water (hourly, daily), m^3; $B_m \Rightarrow \max$ is ventilation (hourly, daily), m^3.

Given potential complexity of solving such multicriteria tasks, some of the above minimax criteria can be replaced later by the following limiters (24-27):

$$P \geq P^{\min}, \quad (24)$$

$$B \geq B^{\min}, \quad (25)$$

$$B_\partial \geq B_\partial^{\min}, \quad (26)$$

$$B_m \geq B_m^{\min}, \quad (27)$$

where $P^{\min}$, $B^{\min}$, $B_\partial^{\min}$, $B_m^{\min}$ are thresholds for the corresponding parameters (e.g. planned daily values).

The value of power consumption in the system as a whole or at its separate stages from the local criterion can be similarly redefined in the form of:

$$RE = f\left(P, B, B_\partial, B_m\right), \quad (28)$$

where $f\left(\bullet\right)$ is some function or approximation.

Block 3 checks whether an enterprise has a valid agreement (contract) with the power generating company for electricity supply. If there is such an agreement, the algorithm is prolonged from the next block (Block 4). If there is no agreement, algorithm is terminated and either further calculations can be done on a general basis or such an agreement can be concluded later on.

Similarly, conditional Block 4 checks whether the enterprise has a valid agreement (contract) with a power transporting company for power transportation. If there is such an agreement, the algorithm is prolonged from the next block (Block 5). If there is no agreement, this algorithm is terminated, and either further calculations can be done on a general basis or such an agreement can be concluded later on.

Block 5 enables selecting a category of an industrial consumer ("A" or "B"), i.e.

Cat = {"A", "B"}.

Block 6 allows an enterprise to choose (order from a power generating company) a required tariff for a day (T_d) and the planned amount of power consumption. It is desirable to maintain the ordered volume as accurately as possible, because under-fulfilling or vice versa, exceeding the ordered volume may cause potential economic losses of the enterprise.

Considering the requirements for the declared power consumption, an integrated evaluative indicator (T_Σ) is formed in Block 7, considering the actual power consumption and a special penalty function. A useful feature of the latter is that the value of the penalty should approach 0 (either no or minimal penalty) if there are no deviations. With positive or negative deviations, the function begins to increase sharply (i.e. the penalty is maximized). An example of a penalty function is the following:

$$f^{pen} = r \sum_{i=1}^{NS} \left[\frac{\left| \overline{T_i} - T_i^{add} \right| + (\overline{T_i} - T_i^{add})}{2} \right]^2, \quad (29)$$

where: $\overline{T_i}$ is the average daily value of the *i*-th tariff; T_i^{add} is restriction on deviations in power consumption when applying the *i*-th tariff to the system; *NS* is the number of set tariff intervals; *r* is the penalty coefficient (an empirically selected integer).

$$T_\Sigma = E_d + f^{pen}(T_d, RE, HP), \quad (30)$$

where E_d is assessment of actual power consumption.

Block 8 is actually designed to select the optimal strategy (*s*) to control power consumption through solving an optimization problem with certain parameters of state vectors of (19), (28). Parameters of ore flows, air, drainage and ventilation (P, B, B_∂, B_m) with the minimum value of the target functional are actual solution to the problem.

$$s = \underbrace{ArgMIN[T_\Sigma]}_{P,\ B,\ B_\partial,\ B_m}, \quad (31)$$

Final Block 9 of the algorithm actually ceases the corresponding calculation and allows implementing more complex smart approaches to controlling electric power consumption. The second component of the solution – selection of control devices and parameters – is to be developed next.

RESEARCH RESULTS

In accordance with the above methods, we present calculations of specific technological parameters of drainage facilities at Hvardiiska underground mine (Kryvyi Rih) as an example.

Let us divide the research process into components according to the proposed methodology considering statistical indices of power consumption at Hvardiiska underground mine (Kryvyi Rih) [32] (Table 1).

Table 1. **Statistical indices of power consumption at Hvardiiska underground mine (Kryvyi Rih)**

Year	Y kW*h	$X1$, m^3/h	$X2$, m	$X3$, kW	$X4$, pcs
2012	44219.22	184.6	527	800	2
2013	41181.33	177.3	1200	800	2
2014	43544.69	185.3	1200	250	3
2015	42983.44	168.6	1200	250	3
2016	43784.32	169.9	1350	315	3
2017	47673.55	167.5	1350	315	3
2018	43547.42	178.2	1350	315	3

Source: **compiled by the authors**

The indicators used for calculations are highlighted: Y is power consumption, kW*h; $X1$ is water inflow, m^3/h; $X2$ is the level, m; $X3$ is pump capacity, kW; $X4$ is the number of pumps, pcs.

It is known that when using mathematical and statistical methods, linear regression models are most often selected not only to simply determination of parameters, but also to analyze adequacy of obtained models.

Let us select the structure of the regression equation to be linear:

$$y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 + a_3 \cdot x_3. + a_4 \cdot x_4$$

Processing the given statistics results in the following calculations:

$$a_o = -15.522;\ X1 = 0.982;\ X2 = 0,5;$$
$$X3 = 0.391;\ X4 = -7.588.$$

i.e. pure regression coefficients:

$$a_0 = -15.522;\ a_1 = 0.982;\ m_2 = 5.001;$$
$$a_3 = 0.391;\ a_4 = -7.588.$$

Thus, the following equation of multiple regression is obtained:

$$\hat{y} = -15.522 + 0.982 \cdot x_1 + 0.5 \cdot x_2 + 0.391 \cdot x_3 - 7.588 \cdot x_4. \quad (32)$$

The regression equation shows that with a 1 % increase in water supply (with unchanged specific weight of other factors), power consumption increases by 0.982.

Validity of the model is checked by relative deviations for each observation. The average approximation error does not exceed 10%. According to this methodology, individual correlation coefficients characterizing relationship between the result and the corresponding factor with eliminated influence of other factors included in the regression equation are calculated.

The coefficient of multiple correlations is determined through matrices of pair correlation coefficients

$$R_{yx1x2x3x4} = 0.981.$$

The multiple correlation coefficients indicate a significant relationship between the entire set of factors and the result [21, 22].

The uncorrected multiple determination coefficients evaluate the fraction of the result variance due to the factors presented in the equation in the total variation of the result. Here, this fraction makes 98.1 % and indicates a high degree of conditionality of the result variation of factors, in other words, a very close relationship of the factors and the result.

The corrected coefficient of multiple determination $\hat{R}^2 = 0.93$ conditions a close relationship considering freedom degrees of total and residual variances. Assessment of relationship like this, which does not depend on the number of factors, can be compared according to different models with a different number of factors. Both coefficients indicate a high determinability of the result in the model by factors.

Validity of the regression equation as a whole and the indicator of closeness of relationship produce the F-criterion:

$$F = 40.18;\ F_{table} = 4.12.$$

The actual value is greater than that in the table, so probability to accidentally obtain such an F-criterion value does not exceed the permissible significance level of 5 %. Thus, the resulting value is not random, it is formed under the influence of significant factors and i.e. the statistical significance of the entire equation and the indicator of closeness of the relationship are confirmed.

Let us evaluate statistical significance of pure regression parameters using the Student t-criterion:

$$t_{b1} = 2.158;\ t_{b2} = 4.159;\ t_{b3} = 3.431;\ t_{b4} = 8.051;$$
$$t_{table} = 4.12 \text{ at } f = 0.7,\ \rho = 0.95.$$

The calculated values of the criteria are greater than the table ones, and therefore the parameters a_1, a_2, a$_3$, a_4 are statistically significant.

By means of individual F-criteria we evaluate efficiency of including multiple regression of factors x_1, x_2, x_3, x_4 into the equation:

$$F_{x1} = 4.658;\ F_{x2} = 5.025;$$
$$F_{x3} = 11.775;\ F_{x4} = 64.822;$$
$$F_{table} = 4.12 \text{ at } f_1 = 0.7,\ f_2 = 7,$$

that confirms significance of the above factors.

In other words, an increase in the factor feature ($X1$) – water inflow – by 1 % causes an increase in power consumption by 0.98. Accordingly, an increase in the factor feature ($X3$) – pump power, kW – by 1 % causes an increase in power consumption by 0.56. As for the factor feature (X4) – the number of pumps, pcs., power consumption decreases by 7.5 due to their increased number.

The partial correlation coefficients are:

$$r_{yx1} = 0.272,\ r_{yx3} = 0.143,\ r_{yx4} = 0.656.$$

According to the Chaddock scale, the most evident relationship is between $X3$ and Y, the relationship between $X1$ and Y, $X3$ and Y is weak.

Analytical analysis of the model, namely multifactor degree one (19) is carried out:

– boundary efficiency characterizing an increase of the maximum increment in power consumption by one in case of changing each factor by one.

Thus, the change in water intake causes an increase in power consumption by 0.982; that of the level – by 0.5; pump capacity – 0. 391; the number of pumps causes a decrease in power consumption by 7.588;

– the calculated total elasticity indicates that with a 1 % increase in all factors considered power consumption for drainage facilities at iron ore mining enterprises is 5.715 %.

The calculated determination indices confirm validity of selecting nonlinear models.

Thus, the obtained model ratios can be applied to iron ore mining enterprises' operation to form appropriate managerial decisions.

The above algorithm enables modeling control over and optimal power consumption by drainage facilities at Rodina underground mines (Kryvyi Rih).

Fig. 3 visualizes the results of modelling in MATLAB (Fuzzy Logic Toolbox) using a fuzzy logic controller (FLC) and minimax control (minimization of power supply with maximization of ore output and/or drainage) based on optimal setting (Setting 3*). The indicator of the system reaction (ACS reaction) demonstrates quality of solving the control task (i.e. setting) considering the selected power tariff.

The results of the modeling analysis indicate that:

– application of minimax control (minimization of power supply with maximization of ore output and/or drainage) causes a designed increase in power consumption by about 1.5 %, which is fully compensated by an increase in daily iron ore production and potential sales revenue;

– application of control based on optimal settings maintains the planned daily ore production, but at the same time the total daily costs of power consumed reduce by 28.39 % due to more efficient distribution of ore/water flows and appropriate power consumption at technological stages according to the selected tariff.

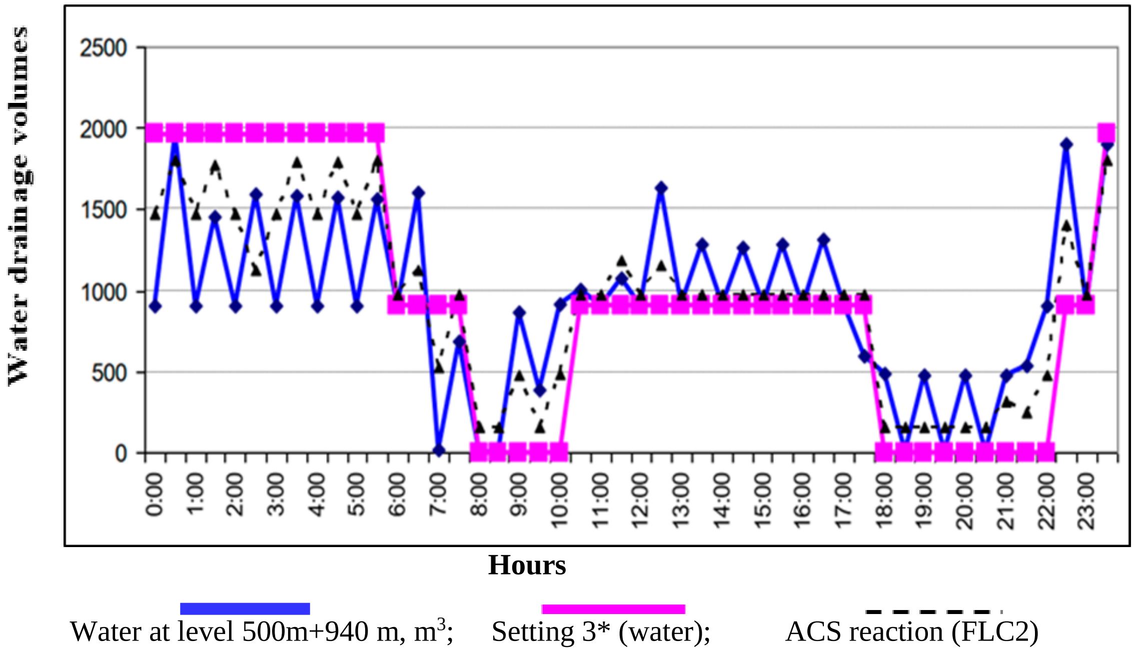

Fig. 3. Optimal power consumption option for drainage facilities at Rodina underground mine (Kryvyi Rih)

Source: **compiled by the authors**

CONCLUSIONS

The conducted studies allow drawing the following conclusions.

1. Mathematical modeling of groundwater drainage at iron ore underground mines presented as a stochastic process enables determining the most significant power parameters, which are subject to the accidental influence of a number of disturbing factors, thus assessing their impact on this process. Drainage parameters built on average values only should be supplemented with some new ones that characterize their scattering for a certain period. Analysis of the models provides the basis for making effective managerial decisions to solve the problems of improving power consumption by drainage facilities at underground mines within specific iron ore enterprises.

2. Computer modeling results are verified through real statistical parameters of typical iron ore underground mines of Ukraine using control methods with optimal settings that always leads to a 20%-28% reduction in power costs through redistributing power flows according to daily zone tariffs simultaneously maintaining planned indices of iron ore production.

3. Application of fuzzy logic and correlation analysis enable developing algorithms of *the ACS of electric power consumption* for a typical iron ore mine. They include stages of fuzzification, logical inference and defuzzification and are different from the existing ones in the varied number of control actions determined by correlation between controlling and controlled parameters of basic production stages and selected criteria of the system functioning. The above allows implementing automated decision-making as part of the drainage control system under nonlinear characteristics, incomplete information and multi-channel control.

4. *The ACS of electric power consumption* with fuzzy varied three-channel control over mine drainage allows reducing power costs with the simplified time-of-day tariff due to more effective redistribution by daily intervals according to the data on Rodina underground mine. Meanwhile, with increased daily power consumption, total costs decrease.

5. The innovative approach, which combines conventional multifactor regression modelling with modern digital methods, namely formation of input-output parameters of *the ACS for drainage facilities*, provides managers with an effective tool for controlling power consumption modes of consumers to ensure overall energy efficiency of iron ore mining enterprises.

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Інформаційні аспекти моделі споживання електричної енергії головними водовідливними комплексами залізорудних підприємств

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АНОТАЦІЯ

Робота присвячена дослідженню варіативних інформаційних підходів до моделювання споживання електричної енергії головними водовідливними комплексами гірничорудних підприємств з підземним способом видобутку залізної руди (шахти, рудники тощо). Сформовані методичні рекомендації щодо використання розроблених моделей. В роботі досліджені загальні методологічні підходи щодо формування моделей, в яких пов'язані як показники споживання електричної енергії водовідливними комплексами, так і відповідні вартісні показники. Доведено доцільність логістики формування системи моделей, а саме поєднання класичного багатофакторного регресійного моделювання з застосуванням сучасних цифрових методів моделювання – автоматизованими системами керування (АСК) водовідливними комплексами. Докладно визначені принципи побудови нечітких регуляторів, а також алгоритми їх роботи в умовах багатоканального управління. Запропоновано удосконалений варіант на основі застосування нечіткої логіки і кореляційного аналізу - алгоритми роботи «АСК електро- та енергоспоживання». Наведено приклад розбудови «дорожньої карти» реалізації побудови узагальненого алгоритму АСК енергетичними потоками для двох актуальних наразі випадків: при вибірковому тарифі з обмеженнями на добове енергоспоживання на підставі угод, та при змінному тарифі. Виявлено, що використання погодинного тарифу з умовним розподілом його на («Ніч/Пік») замість три ставкового («Ніч/Напів пік/Пік») одноразово веде до збільшення добових витрат на спожиту електроенергію на майже тринадцять відсотків при одно канальному регулюванні

потоком руди і, відповідно, на сім відсотків при двоканальному управлінні потоком руди і водовідливом одночасно. Застосування нечітких регуляторів дозволяє мінімізувати ці втрати.

Ключові слова: нечітка логіка; кореляційний аналіз; залізорудне підприємство; головні водовідливні установки; споживання електричної енергії; багатофакторне регресійне моделювання

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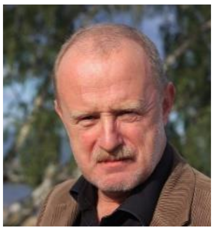

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